Detection of TeV photons from the active galaxy Markarian 421

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PHOTONS of TeV energy have been observed from a few sources in our Galaxy, notably the Crab Nebula[1]. We report here the detection of such photons from an extragalactic source, the giant elliptical galaxy Markarian 421. Mk 421 has a nucleus of the BL Lacertae type[2,3], and emission from it has been observed at radio[4–6], optical[3,6] and X-ray[6–8] frequencies, and most recently in the MeV–GeV bands, by the EGRET detector aboard the Compton observatory[9]. In March–June 1992, we observed Mk 421 with the Whipple Observatory γ-ray telescope[10], a ground-based detector that images Cerenkov light from air showers, and found a signal with statistical significance of 6σ above background. The flux above 0.5 TeV is 0.3 of that from the Crab Nebula. The source location agrees with the position of Mk 421 within the angular uncertainty (6 arc minutes) of the Whipple instrument. The fact that we have observed this relatively nearby source (redshift $z = 0.031$), whereas active galaxies and quasars that are brighter at EGRET energies but more distant have not been detected in the TeV energy range, may be consistent with suggestions[11,12] that TeV photons are strongly attenuated by interaction with extragalactic starlight.

The very-high-energy γ-ray telescope[10] at the Whipple Observatory images Cerenkov light from air showers on a two-dimensional array of 109 fast photomultipliers with a pixel size of 0.25°. Monte Carlo simulations[13,14] and repeated observations of the Crab Nebula[15,16] demonstrate that the Cerenkov light images of air showers induced by γ-rays can be reliably distinguished from those induced by cosmic-rays (that is, nucleons).

The most sensitive technique yet used by the Whipple group for this purpose ('supercuts'[17]) uses four parameters to characterize the roughly elliptical shower image. Two of these are the root-mean-square length and width of the ellipse. A third, 'distance', is the angular distance of the centroid of the shower image from the assumed source location in the image plane. A fourth parameter, 'alpha', gives the orientation of the image. Alpha is defined to be the angle between the major axis of the shower image and a line from its centroid to the assumed source location in the image plane. For γ-ray showers from a point-like source, alpha should be near 0° because the elliptical images point to the location of the source in the image plane. The supercuts procedure[17] selects showers with small size, at distances from 0.51° to 1.1°, and with values of alpha <15 degrees.

In Fig. 1*a*, the alpha distributions for on-source and off-source observations of Mk 421 are compared after the other supercuts selection criteria have been satisfied. For the region of alpha <15 degrees there is a 6.3σ excess, with 302 on-source showers and 166 off-source showers. These observations were made between 24 March and 2 June 1992 for a total of 7.5 hours on-source and an equal amount of time off-source. The excess corresponds to an average flux of 1.5×10^{-11} photons $cm^{-2}\,s^{-1}$ above 0.5 TeV, equivalent to 0.3 times that of the Crab Nebula. If one assumes isotropic emission at a distance of 124 Mpc, then the corresponding luminosity is $\sim 10^{43}$ erg s^{-1}. But as Mk 421 is known to show jet-like behaviour, the actual TeV luminosity may be considerably less.

For comparison, the alpha distributions for the previously reported observations of the Crab Nebula[17] are shown in Fig. 1*b*. For the Crab Nebula the excess has a statistical significance of 34σ. For both sources, the data of Fig. 1 have been restricted to observations at elevations greater than 55°. The similarity between the Mk 421 excess in the small-angle region of Fig. 1 and the corresponding excess for the Crab Nebula corroborates the Mk 421 signal. As a measure of the stability of the Whipple detector, the on-source and off-source datasets contained 77,181 and 76,761 raw, uncut showers, respectively, a difference of only 0.55%. We have investigated the possibility that the excess shown in Fig. 1*a* may be a systematic effect related to the on- and

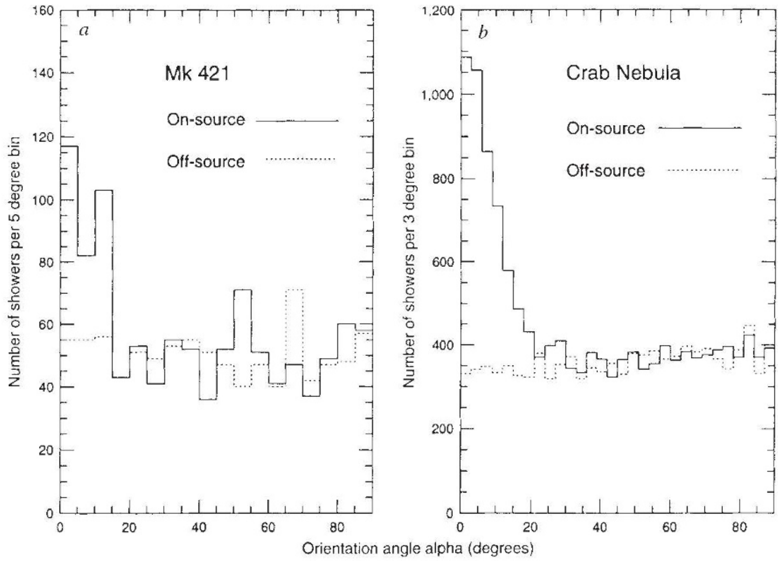

FIG. 1 On- and off-source orientation angle ('alpha') distributions for *a*, Mk 421 and *b*, Crab Nebula. The distributions are for those showers for which the other supercuts selection criteria[16] have been satisfied. The supercuts selection value for alpha is 15°.

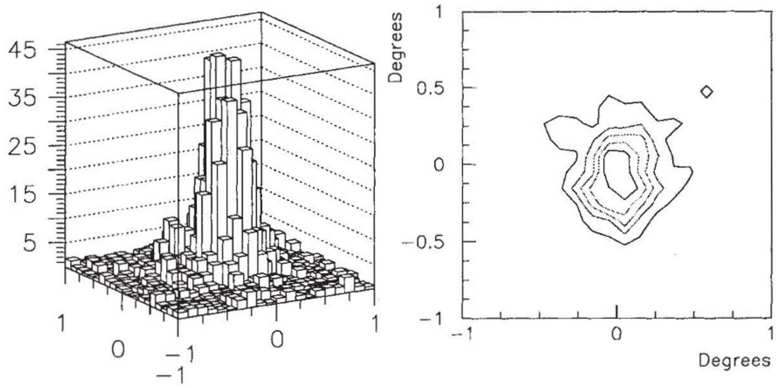

FIG. 2 Maps of the on-source observations for Mk 421 made according to the prescription of ref. 18, Figs 4 and 5. The peak intensity lies within 0.1° of the known location of Mk 421.

off-source star fields but find that control observations of other star fields with similar characteristics show null results when they are subjected to the supercuts analysis.

From the observations a two-dimensional map of the source region[18] may be created. Figure 2 shows the map from the observations of Mk 421. The centre of the field of view corresponds to the known direction of the source. The peak seen is within 0.1° degree of this direction.

Mk 421 is only the second source to be seen by the Cerenkov imaging technique and the first extragalactic source. The power-law energy spectra reported by EGRET (C. E. Fichtel, personal communication) for the active galactic nuclei that it has detected are uniformly hard, with differential photon spectral indices of two or less. For Mk 421 the differential power-law index is estimated as ~1.8 (Y. C. Lin, personal communication on behalf of the EGRET group). The spectral index implied by joining the 100-MeV point with the flux reported here at 0.5 TeV is 2.0. In general, the EGRET spectra, extrapolated to TeV energies, would imply γ-ray intensities greater than that of the Crab Nebula for the brighter sources. Nikishov[11] and Stecker *et al.*[12] have pointed out that absorption of TeV photons by the general background of starlight and infrared photons is severe for sources at $z \approx 1$. Even for a closer source such as 3C 273 at $z = 0.158$, the optical depth at 1 TeV is of order unity. Mk 421, at $z = 0.031$, would be relatively unaffected except at energies above a few TeV. We regard this effect as a possible explanation for the detection of Mk 421 and the failure to detect, as yet, other active galactic nuclei that are brighter than it at GeV energies. But in view of the variability observed for such sources, this cannot yet be confirmed. A preliminary estimate of the spectrum of Mk 421 from our data indicates that the excess is generally confined to energies less than 1.5 TeV. □

Received 16 June; accepted 29 June 1992.

1. Weekes, T. C. *Phys. Rep.* **160**, 1–121 (1988).
2. Ulrich, M.-H., Kinman, T. D., Lynds, C. R., Rieke, G. H. & Ekers, R. D. *Astrophys. J.* **198**, 261–266 (1975).
3. Maza, J., Martin, P. G. & Angel, J. R. P. *Astrophys. J.* **224**, 368–374 (1978).
4. Owen, F. N., Porcas, R. W., Mufson, S. L. & Moffett, T. J. *Astr. J.* **83**, 685–696 (1978).
5. Zhang, F. J. & Bååth, L. B. *Astr. Astrophys.* **236**, 47–52 (1990).
6. Mufson, S. L., Hutter, D. J., Kondo, Y., Urry, C. M. & Wisniewski, W. Z. *Astrophys. J.* **354**, 116–123 (1990).
7. Mushotzky, R. F., Boldt, E. A., Holt, S. S. & Serlemitsos, P. J. *Astrophys. J.* **232**, L17–L19 (1979).
8. George, I. M., Warwick, R. S. & Bromage, G. E. *Mon. Not. R. astr. Soc.* **232**, 793–808 (1988).
9. Michelson, P. F. *et al. IAU Circ.* No. 5470, 1 (1992).
10. Cawley, M. F. *et al. Exp. Astr.* **1**, 173–193 (1990).
11. Nikishov, A. J. *Sov. Phys. JETP* **14**, 393–394 (1962).
12. Stecker, F. W., De Jager, O. C. & Salamon, M. H. *Astrophys. J.* **390**, L49–L52 (1992).
13. Hillas, A. M. in *Proc. 19th int. Cosmic Ray Conf. (La Jolla)* **3**, 445–448 (1985).
14. Macomb, D. J. & Lamb, R. C. in *Proc. 21nd int. Cosmic Ray Conf. (Adelaide)* **2**, 435–438 (1990).
15. Weekes, T. C. *et al. Astrophys. J.* **342**, 379–395 (1989).
16. Vacanti, G. *et al. Astrophys. J.* **377**, 467–479 (1991).
17. Punch, M. *et al.* in *Proc. 22nd int. Cosmic Ray Conf. (Dublin)* **1**, 464–467 (1991).
18. Akerlof, C. W. *et al. Astrophys. J.* **377**, L97–L100 (1991).

ACKNOWLEDGEMENTS. We thank K. Harris and T. Lappin for help in obtaining these observations. We acknowledge support from the U.S. Department of Energy, NASA, the Smithsonian Scholarly Studies Research Fund and EOLAS, the scientific funding agency of Ireland.

Predicted response of stream chemistry to acid loading tested in Canadian catchments

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SHORT-TERM acidification of lakes and streams can cause biological damage by lowering pH and increasing concentrations of inorganic aluminium[1–4]. Storms laden with acids and sea salts, rapid melting of acidic snow and remobilization of acids stored in catchment soils can cause episodes of acidification lasting from hours to months. These episodes can help to reveal the mechanisms that regulate catchment runoff chemistry[5–7]. Here we use extreme, climatically triggered acidification episodes in 18 intensively monitored streams in Canada to test a geochemical theory[8] that predicts the chemical response of catchments to changes in acid loading. At all 18 catchments, changes in base cation (Ca^{2+}, Mg^{2+}, Na^+, K^+, NH_4^+) concentrations offset about 75–95% of the observed changes in acid anion ($SO_4^{2-}, NO_3^-, Cl^-, OA^-$) levels; increases in hydrogen and aluminium ions and decreases in bicarbonate accounted for the remaining 5–25%. In response to equal acid anion increases, however, some catchments released over 35 times more H^+ or 50 times more inorganic aluminium than others. The observed chemical responses to shifts in acid anion loading agreed with *a priori* geochemical predictions derived[8] from the chemical composition of runoff, indicating that catchment vulnerability to acidification can be assessed, in advance, directly from surveys of lake and stream chemistry.

The theory tested here is a simple mechanistic method for predicting catchment response to changing acid anion concentrations directly from runoff chemistry[8]. The governing equations resemble those underlying many acidification computer models[9–12], but they are solved analytically, yielding catchment acidification response as a function of concentrations in catchment runoff. In a charge balance for typical acid-sensitive waters

$$\begin{aligned}2[SO_4^{2-}]+[NO_3^-]+[Cl^-]+OA^- &= 2[Ca^{2+}]+2[Mg^{2+}]+[Na^+]+[K^+]+[NH_4^+]+[H^+]\\ &\quad +3[Al^{3+}]+2[Al(OH)^{2+}]+[Al(OH)_2^+]+2[AlF^{2+}]\\ &\quad +[AlF_2^+]-[HCO_3^-]-[OH^-]-[F^-]+\cdots \end{aligned} \quad (1)$$